LAWRENCE
LIVERMORE
NATIONAL
LABORATORY

UCRL-JRNL-204517

The National Ignition Facility

G. H. Miller, E. I. Moses, C. R. Wuest

June 7, 2004

Optical Engineering

The National Ignition Facility

George H. Miller, Edward I. Moses, Craig R. Wuest

Lawrence Livermore National Laboratory, P.O. Box 808 L-466, Livermore, CA 94551

ABSTRACT

The National Ignition Facility (NIF) at Lawrence Livermore National Laboratory is a stadium-sized facility that, when completed in 2008, will contain a 192-beam, 1.8-Megajoule, 500-Terawatt, ultraviolet laser system together with a 10-meter-diameter target chamber and room for 100 diagnostics. NIF is the world's largest and most energetic laser experimental system and will provide a scientific center to study inertial confinement fusion and matter at extreme energy densities and pressures. NIF's energetic laser beams will compress fusion targets to conditions required for thermonuclear burn, liberating more energy than required to initiate the fusion reactions. Other NIF experiments will study physical processes at temperatures approaching 10^8 K and 10^{11} bar; conditions that exist naturally only in the interior of stars and planets. NIF has completed the first phases of its laser commissioning program. The first four beams of NIF have generated 106 kilojoules in 23-ns pulses of infrared light and over 16 kJ in 3.5-ns pulses at the third harmonic (351 nm). NIF's target experimental systems are being commissioned and experiments have begun. This paper provides a detailed look the NIF laser systems, laser and optical performance, and results from recent laser commissioning

shots. We follow this with a discussion of NIF's high-energy-density and inertial fusion experimental capabilities, the first experiments on NIF, and plans for future capabilities of this unique facility.

Keywords: High Energy Density Physics, Inertial Confinement Fusion, Laboratory Astrophysics, Solid State Lasers

1. INTRODUCTION

The National Ignition Facility (NIF), under construction at the Lawrence Livermore National Laboratory (LLNL) for the U.S. Department of Energy and National Nuclear Security Administration (NNSA), will be a scientific center for the study of inertial confinement fusion and the physics of extreme energy densities and pressures. Construction of the building that houses the laser system was completed in September 2001, and the installation of all 192 ultra-clean and precision aligned beampath enclosures was completed in September 2003. Figure 1 shows a recent photograph of the exterior of NIF Laser and Target Area Building. In late 2002, NIF began activating its first four laser beamlines. By July 2003, NIF had delivered world-record single-laser energy performance in primary (1.06 micron), second, and third harmonic wavelengths. When completed in 2008, NIF will provide up to 192 energetic laser beams to compress deuterium-tritium fusion targets to conditions in which they will ignite and burn, liberating more energy than is required from the laser to initiate the fusion reactions. NIF experiments will allow the study of physical processes at temperatures approaching 100 million K and 100 billion times atmospheric pressure. These conditions exist naturally only in the interior of stars and in nuclear weapons explosions. [1-5]

Detailed descriptions of NIF's laser architecture and the performance of the laser system have been presented recently.[6-23] We briefly describe here some of the key features of the NIF architecture that distinguish it from previous large laser systems such as Nova and Shiva at LLNL, and Omega at the University of Rochester Laboratory for Laser Energetics.[7] As shown in Figure 2, earlier inertial confinement fusion (ICF) lasers were designed with single-pass Master Oscillator/Power Amplifier (MOPA) chains that held the energy density or fluence constant at the output of each amplifier. This design provided for good energy extraction while staying below the fluence limit for damage. The output from one amplifier was matched to the input of the next amplifier by relay telescopes that served a number of functions. The relay telescopes expand the beam area as required from amplifier to amplifier, re-image the near field of the beam at each amplifier, thus reducing the impact of diffraction, and provide for support of pinholes at the foci of the telescopes. These pinholes are used to strip high-frequency spatial components from the propagating beams. MOPA chains that were typical of those for Shiva, Nova, and Omega typically are characterized by many different amplifier and telescope designs, good gain, moderately good extraction efficiency, poor packing density, and low technical risk.

To implement the next generation laser architecture for ICF, the search began in the late 1980's for a laser design that could provide substantially more output energy at substantially lower cost while continuing to meet all of the requirements for beam quality. The most appealing approach was to purchase only the largest final amplifiers and use several earlier passes through that amplifier for the required high gain to go from a small master oscillator to the final energy-extracting pass. This led eventually to the basic design of the NIF multipass chain shown in Figure 3. In addition to a single amplifier design, the NIF multipass chain is characterized by good gain, good extraction efficiency, and high packing density. The design issues are discussed further in a companion paper in this issue of Optical Engineering, and elsewhere.[7,24,61]

At the time of its conception,[24] some development was needed in order to implement the NIF multipass design. The technologies needing development included an optical switch, deformable mirror, frequency conversion crystals and mirrors, and polarizers all at a beam aperture of 40 x 40 cm^2. The technologies needing development included a full aperture optical switch, a full aperture deformable mirror, full aperture frequency conversion crystals and full aperture mirrors and polarizers. All were successfully developed and are now in regular use in NIF.[9] The active element of the switch is a KDP crystal. Voltage must be applied across this switch crystal in the direction of beam propagation, requiring the electrodes to be fully transparent and tolerant of high fluence laser light. Plasma on either side of the crystal provides these electrodes, thus giving rise to the name of the switch, Plasma-Electrode Pockel's Cell (PEPC).[20]

Among the many challenges in designing and building NIF has been the design, engineering, construction, and commissioning of what is arguably the largest precision optical instrument ever built. Optics research, and laser science and engineering have taken place at NIF on a scale never before attempted. The optics and optical systems for NIF are the result of over thirty years of laser and optical materials research and development at national laboratories, universities,[25,26] and in private industry throughout the world. On NIF there are more than 7500 large optics of 40 cm or greater transverse size including laser amplifier glass slabs, lenses, mirrors, polarizers, and crystals. An additional 26,000 smaller optical components are used in NIF. The total area of precision optical surfaces in NIF is nearly 4,000 square meters.[6] NIF scientists and engineers have worked closely with industry and academia to develop new production processes for optics manufacturing and finishing. For example NIF laser glass slabs are produced using a novel continuous pour production method developed jointly with two glass vendors. This production method has resulted in very high quality laser glass amplifier slabs that meet NIF's requirements for cost, schedule and technical performance. Over 3,000 meter-size glass slabs have been produced for NIF using this technique.[27,28]

NIF's laser systems are precisely aligned to better than 250 microns and point accuracy on NIF laser beams is 50 microradians. This precision placement had to be achieved over laser beam path lengths of 350 meters. In addition, NIF's beampath is required to be extremely clean to ensure that laser optics remain free of dust particles. Special robotic transport and handling systems are used for all of NIF's modular optical components, which are assembled into large phone-booth sized line-replaceable units or LRUs.

We have now installed the optics and mechanical utilities required to activate 4 of NIF's laser beams. Over the past year we have carefully studied the performance of these laser beams and we have carried out over 180 system shots. In addition, approximately 30% of the 7,500 meter-scale optics required for NIF have been completed as of the end of

November 2003. These optics have been fabricated to NIF's specifications utilizing deterministic processes that were developed as a result of our multi-year research program. After a brief description of NIF's laser systems we will present some quantitative results on laser performance. In addition to the laser system, the first diagnostic systems to be used for both laser performance measurements and physics experiments have been installed and commissioned. These include static x-ray imaging, gated and streaked x-ray detectors mounted on the NIF target chamber, and a full-aperture backscatter diagnostic that images scattered light through the final optical beampath of the first four beams. With this initial suite of diagnostics, NIF experimenters have completed the first studies related to laser-plasma interactions applied to ignition hohlraum energetics and hydrodynamics.[29]

2. A DESCRIPTION OF NIF

The NIF laser system is shown schematically in Figure 4. NIF consists of a number of sub-systems including amplifier power conditioning modules, the injection laser system consisting of the master oscillator and preamplifier modules, the main laser system along with its optical components, the switchyards, and the 10-meter target chamber and its target and diagnostic experimental systems. The entire laser system, switchyards, and target area is housed in an environmentally controlled building. An integrated computer control system is located in the core of the facility to monitor, align, and operate the more than 60,000 control points required for NIF's operation.[30] A large cleanroom facility, the Optics Assembly Building is located at one end of NIF for assembling and installing the precision optical and opto-mechanical components that make up the NIF laser system. On the opposite end of the facility the Diagnostics Building houses experimenters, experimenter data acquisition systems, and target preparation and storage areas.

NIF's laser system is comprised of 192 high-power laser beams. For inertial fusion studies these laser beams will produce 1.8 million joules (approximately 500 trillion watts of power for 3 nanoseconds) of laser energy in the near-ultraviolet (351 nanometer wavelength). This is approximately 60 times the energy available in the Nova laser, which was operated at LLNL between 1983 and 1999 and Omega Laser at the University of Rochester's Laboratory for Laser Energetics.

Figure 5 schematically shows one of the 192 laser beams, detailing the line-replaceable units that are used along the beam path. A NIF laser beam begins with a nanojoule energy laser pulse from the master oscillator and a diode-pumped fiber amplifier system that can provide a variety of pulse shapes suitable for a wide range of experiments, from complex high contrast pulses for ICF implosions to high-energy extended pulses. The master oscillator pulse is shaped in time and then transported to preamplifier modules (PAMs) for amplification and beam shaping. Each PAM first amplifies the pulse by a factor of one million (to about one millijoule) and then boosts the pulse once again by a factor of 20,000, this time to a maximum of 10 joules, by passing the beam four times through a flashlamp-pumped amplifier. There are a total of 48 PAMs on NIF, each feeding a "quad" of four laser beams. Figure 6 shows a photograph of NIF's Master Oscillator Room and Figure 7 show a NIF PAM.

From the PAM the laser beam next enters the main laser system, which consists of two large amplifier units – the power amplifier, and the multi-pass or main amplifier. These amplifier systems are designed to efficiently amplify the input pulse from the PAM to the mission-required power and energy, maintaining the input beam's spatial, spectral, and temporal characteristics. The amplifiers, with 16 glass slabs per beam, are arranged with 11 slabs in the main amplifier section and five slabs in the power amplifier section (the power amplifier can actually accommodate 7 slabs per beam if necessary for future applications). Together, these amplifiers provide 99.9% of NIF's power and energy. The amplifiers use 42 kilogram slabs, measuring 46 cm x 81 cm x 4.1 cm, of neodymium-doped phosphate glass set vertically on edge at Brewster's angle to minimize reflective losses in the laser beam.[27,28] The slabs are stacked four high and two wide to accommodate a "bundle" of eight laser beams (see Fig. 8).

The slabs are surrounded by vertical arrays of flashlamps, measuring 180 cm in length. A total of 7680 flashlamps and 3072 glass slabs are required for NIF's 192 laser beams. Each flashlamp is driven by 30,000 joules of electrical energy from the Power Conditioning System (PCS), which consists of the highest energy array (about 400 megajoules) of electrical capacitors ever assembled.[31] The intense white light from the flashlamps excites the neodymium in the laser slabs to provide optical gain at the primary 1.06 micron infrared wavelength of the laser. Some of the energy stored in the neodymium is released when the laser beam passes through the slab. Advances in glass amplifier technology allow NIF to operate with less than twice the number of flashlamps than Nova even though the laser system will produce 60 times more output energy. The flashlamps are cooled between shots, along with the amplifier slabs, using nitrogen gas so that NIF can be fired once every four hours. Figure 8 shows how flashlamps and laser glass are assembled and installed into the NIF beampath.

A key component in the laser chain is an optical switch called a plasma-electrode Pockels cell (PEPC), which allows the beam to pass four times through the main amplifier cavity.[20,32] This device uses electrically induced changes in the refractive index of an electro-optic crystal, made of potassium dihydrogen phosphate (KDP). When combined with a polarizer, the PEPC allows light to pass through or reflect off the polarizer. The PEPC will essentially trap the laser light between two mirrors as it makes four one-way passes through the main amplifier system before being switched out to continue its way to the target chamber. The PEPC consists of thin KDP plates sandwiched between two gas-discharge plasmas that, although having no effect on the laser beam passing through the cell, serve as conducting electrodes, allowing the entire surface of the thin crystal plate to charge electrically in about 100 nanoseconds so the entire beam can be switched efficiently. Figure 9 shows a four-cell PEPC (optical switch) in operation that will be oriented vertically in a single unit when inserted into NIF's beampath.

All major laser components are assembled in clean, pre-aligned modules called line-replaceable units or LRUs, shown in Figure 5. These LRUs contain laser optics, mirrors, lenses, and hardware such as pinhole filter assemblies that are robotically installed into NIF's beampath infrastructure, while maintaining the high level of cleanliness required for proper laser operation. Autonomous guided vehicles carrying portable clean rooms position themselves underneath NIF's beampath enclosures and robotically insert LRUs into the beampath. The installation, integration, and commissioning of the beampath infrastructure at the required cleanliness levels has been successfully accomplished for the more than 120 LRUs required for NIF's first four laser beam lines.

The NIF target chamber and final focusing system is designed with maximum flexibility for experimental users and includes 120 diagnostic instrumentation and target insertion ports. During initial operation, NIF is configured to operate in the "indirect drive" configuration, which directs the laser beams into two cones in the upper and lower hemispheres of the target chamber. This configuration is optimized for illuminating the fusion capsule mounted inside cylindrical hohlraums using x-rays generated from the hot walls of the hohlraum to implode the capsule.[33] Figure 10 shows a recent photograph of the upper half of the target chamber. Each laser entry port allows a quad of laser beams to be focused to the center of the target chamber through a final optics assembly (FOA). The FOA is a precision optical assembly containing optics to provide a variety of beam profiles on target, KDP and deuterated KDP plates to convert the infrared laser light into the ultraviolet, the final focus lens, debris shields and vacuum gate valve for each beam.

3. NIF EARLY LIGHT

NIF construction began in May 1997 and nearly all 192 beampath enclosures are now in place and ready for optics installation. Figure 11 shows the beampath installed in Laser Bay 2. In October 2001 the first laser light from NIF's master oscillator was generated in the master oscillator room located in the central core of the NIF building. This master oscillator has demonstrated the required pulse shaping stability and accuracy for high contrast ignition pulses and other types of laser pulses that are of interest to NIF experimenters. In June 2002 the first preamplifier module was installed in the Laser Bay and routinely amplifies master oscillator pulses to the joule level.

First high energy 3ω laser light to the center of NIF's target chamber was achieved in January 2003 with approximately 1 kilojoule (kJ) of laser energy focused onto a simple foil target. The energetic x-rays emitted from this target were measured with an x-ray pinhole imaging system called the Static X-ray Imager (SXI) mounted on the target chamber. In April 2003 10.6 kJ of 3ω light was produced in four beams and directed to a target in the target chamber. Recently we have delivered 16 kJ of 3ω light in four beams to the target chamber for experiments.[29]

A separate target chamber, known as the Precision Diagnostic System (PDS) is used to fully characterize NIF's 1ω, 2ω, and 3ω laser beam energy, power, and wavefront to validate and enhance computer models that predict laser performance. Any one of the four NIF beams can be directed into the PDS using a robotic mirror and transport system. Figure 12 shows examples of high-energy 2ω and 3ω beams imaged in the near field using the PDS.

At this time NIF's highest 3ω single laser beam energy is 10.4 kJ, equivalent to 2 MJ for a fully activated NIF, exceeding the NIF energy point design of 1.8 MJ. This energy was achieved with 13.65 kJ 1ω drive in a 3.5 ns pulse. We have also conducted a series of shots generating green or 2ω laser light with single beam energy up to 11.4 kJ in a 5 ns square pulse. This is equivalent to nearly 2.2 MJ on target for 192 beams. In July 2003, 26.5 kJ of 1ω light per beam was produced. This energy is 30% greater than the drive energy required for NIF. NIF has now demonstrated the highest energy 1ω, 2ω, and 3ω beamlines in the world. High power campaigns have also been completed with drive power reaching 7 terawatts or about 5 gigawatts/cm^2. Figure 13 details energy and power achieved on a number of 1ω shots conducted through July 2003.

Beam-to-beam synchronization has been measured and adjusted to better than 6 picoseconds, which corresponds to approximately 1 part in 150,000 of the total beampath in NIF. Figure 14 shows this measurement using an x-ray streak camera diagnostic demonstrating NIF's timing performance. Complex shaped ignition pulses as well as ramped and flat-in-time pulses with multi-kJ energies and pulse lengths up to 25 ns have also been demonstrated.

4. NIF OPTICS

Optics production and finishing has been a major area of research over the past three years with an emphasis on making the finishing process more deterministic, reducing the iterative nature of traditional final figuring, and the optic preparation time (grinding and shaping) to prepare the optic for final figuring.[34-41] NIF vendors are now producing substantial numbers of optics that meet our requirements. A significant investment has been made in vendor facilitization programs, resulting in the installation of equipment based on new technology to meet the production capacity and metrology requirements for NIF.[6] Currently NIF's finishing vendors have finished approximately 30% of the optics required for NIF's 192 laser beams. NIF meter-scale optics suitable for high fluence operation with the required wavefront specification are being manufactured at a production rate of over 100 optics per month and we are following a schedule for completing production for all the necessary optics for 192 beam lines by 2007. Figure 15 shows some examples of the large aperture optics being used in NIF.

5. EXPANDING SCIENTIFIC HORIZONS USING THE NATIONAL IGNITION FACILITY

The National Ignition Facility extends the high-energy-density (HED) experimental regimes of current and planned high-energy laser and pulsed-power facilities by a significant amount. Figure 16 displays one measure of NIF's physics reach for temperature and density of materials. NIF will be able to reach conditions of matter that exist in the sun and larger stars, giant planets such as Jupiter, and brown dwarfs that are thought to make up a significant amount of the matter in our universe. With the planned addition of a one-picosecond pulse beam, NIF will be able to reach extreme states of matter more typically associated with nuclear and high-energy-physics accelerator experiments. In this way, NIF can explore the physics of matter at temperatures approaching those that existed in the very early universe.[42]

NIF can drive materials to tens of gigabars for pulse lengths of tens of nanoseconds. Multi-gigabar pressures are achievable using NIF ignition targets, more typically for times of a few ns. Multi-megabar pressures on NIF are achievable at a range of pulse lengths that under certain configurations can be hundreds of nanoseconds.[43] The ability to deliver extended high-energy drive allows experimental measurements of equation of state (EOS), materials at high pressures, hydrodynamics, and radiation transport that have not been possible in prior HED facilities. NIF opens up new fields of study, for example in the area of warm dense matter (WDM) – approximately solid density matter at temperatures in the few eV to tens of eV range.[45] Currently there is no theory that adequately describes WDM. NIF's high-energy laser beams can be tailored for driving relatively large uniform volumes. NIF beams can also be used to provide high x-ray fluences for high signal-to-noise radiography of dense matter. High-energy picosecond laser pulses can provide extremely high brightness and high-energy x-ray backlighter sources for radiographing WDM to fully resolve hydrodynamic features and materials states.[23,45]

Even with the first four beams of NIF, materials can be subjected to tens to one hundred megabars of pressure. Initial EOS experiments with the first four NIF beams are planned in the coming year that have a goal of exceeding 25 Mbar in aluminum[46] in a steady and uniform pressure wave. Isochoric heating with ignition neutrons or high energy petawatt laser-generated ion beams when they become available in the coming decade provides an additional capability for heating materials off the Hugoniot.

6. LABORATORY ASTROPHYSICS

The National Academy of Sciences in the United States has recently recognized the exciting scientific frontiers becoming available at the next generation of high-energy-density experimental facilities.[47] Laboratory-based astrophysics experiments, simulating extreme physics phenomena heretofore inaccessible, are now becoming feasible for the first time. For example, supernovae explosion mechanisms remain uncertain. Recent planar and spherical RT experiments on Nova and Omega showed that instabilities produced in these systems can be quantitatively studied. Figure 17 compares experiments and simulations showing qualitative similarities in their behavior. In fact, a variety of scaled experiments using NIF are possible, studying not only large-scale mixing phenomena associated with supernovae, but also radiatively driven shocks that can lead to 2D jets and 3D spherical shocks observed in astrophysics. Figure 18 displays an astronomical event with a laboratory-scaled experiment. Researchers are assessing NIF's potential for simulating exotic astrophysical systems such as the extended RT systems in the Eagle nebula, immense astrophysical radiative magnetohydrodynamic jets,[48] and even possibly the incredible physical conditions that exist only near the surface of a neutron star.[49] Figure 16 displays examples of these phenomena and associated laser-driven analog experiments. Note the extreme scaling in both time and space between laser experiments and the astrophysical objects in these figures. NIF will provide the capability to study larger-volume targets for longer times and high-fluence. High-energy time-resolved x-ray data will help to validate hydrodynamic models that can be scaled to stellar dimensions and times.

7. IGNITION ON NIF

One of the key missions of NIF is to generate and study thermonuclear ignition and energy gain using the 192 lasers of NIF to compress and heat small capsules containing a mixture of the heavy hydrogen isotopes of deuterium and tritium. Figure 20 diagrams how indirect drive inertial confinement fusion (ICF) is carried out using lasers. Carefully prepared ignition capsules containing the fusion fuel in a thin, very smooth frozen layer surrounding a pressurized DT gas volume are contained in precisely formed plastic or copper-doped beryllium shells. The capsule is suspended in a hollow gold cylinder with laser entrance windows on each end. This structure is called a hohlraum. Carefully focused and temporally-shaped laser beams are directed into the hohlraum through the ends and deliver their energy to the inside walls, generating intense x-rays that uniformly illuminate the capsule. The x-rays ablate the outer surface of the capsule very rapidly. The reaction force from the ablation drives the fusion fuel inward, compressing and heating it to the conditions necessary for thermonuclear fusion reactions to self-initiate. Under the proper conditions, the thermonuclear reactions will propagate outward in a fusion burn, consuming all of the fuel and liberating more energy than was used to drive the target. This type of ICF target is also called an indirect-drive target because the laser beams are not incident directly on the fusion capsule. Indirect-drive targets are advantageous because they tend to smooth out imperfections in the laser drive associated with laser energy and uniformity. However, indirect drive provides less efficient coupling of x-ray energy to the fusion capsule.[33,52] A second approach to ICF is direct drive, where lasers directly illuminate the fusion capsule. The 60-beam Omega laser at the University of Rochester is configured to study direct drive ICF and NIF has been engineered to allow reconfiguration of some of its laser beams to a more symmetric arrangement for direct drive ignition studies in the future.[53] Recent studies are also looking at "polar" direct drive options, in which beam positioning and timing using NIF's indirect drive configuration of lasers can be optimized to directly drive fusion capsules.[54]

In NIF a "point design" ignition hohlraum and capsule has been developed using increasingly sophisticated 3D computer calculations. The most recent calculations, shown in Figure 21, performed on LLNL's ASCI supercomputer system indicates the production of about 20 megajoules of fusion yield in the form of energetic 14-MeV neutrons, x-rays, and gamma rays for about 2 megajoules of UV light delivered from the 192 laser beams.

Prospects for ignition on NIF continue to improve.[52,55] Designs supporting indirect-drive, or x-ray drive of ignition capsules in hohraums are becoming more robust as better physics understanding and better modeling capability, including full 3-dimensional modeling of capsules and hohlraums, allows design trade-off studies to be rapidly performed and design spaces to be optimized. For example, optimization studies have improved plastic capsule performance by a factor of two while allowing ablator roughness to increase by a factor of two, easing fabrication requirements.

New designs using beryllium with graded Cu dopant are particularly robust, with ablator roughnesses being relaxed by as much as a factor of 10-20 over previous designs and newly optimized polyimide designs. In addition, significant progress has been made in fabricating smooth plastic and beryllium/copper capsules that nearly meet these new design specifications.[56]

Precision control of cryogenic D_2 ice smoothness using infrared heating in an isothermal hohlraum has now been demonstrated. Progress is also being made in developing cryogenic hohlraums with convection mitigation and thermal control. Diffusion filling of a capsule in a hohlraum has also been recently demonstrated and integration of infrared layering, thermal shimming, convection mitigation, and characterization in a D_2 test system is under way.[56]

Hohlraums driven with green or 2ω laser light from NIF are also actively being studied.[57] Figure 22 shows recent calculations suggesting that as much as 1.5 MJ of energy may couple to a capsule at 250-eV drive temperature. However, physical data on 2ω laser plasma interactions is limited and more work is needed. NIF 2ω operation has been demonstrated and researchers are studying how to configure some of NIF's early beams for high-energy 2ω LPI studies.

Finally, fast ignition experiments using the Gekko Laser at the University of Osaka, Institute for Laser Engineering, and the Vulcan Laser at Rutherford Appleton Laboratory in the UK are providing tantalizing glimpses of possible low-energy symmetric heating combined with high-power asymmetric drive to induce hot-spot ignition conditions in cone-focused targets.[58,59]

A "proof-of-principle" fast-ignition experiment at NIF is in the design phase. Laser physicists have determined how NIF's current injection laser, main amplifier, and beam transport system could be modified to allow up to 20 high-energy petawatt-class (HEPW) beams to be directed to target chamber center. Initial experiments are being designed to utilize a single kilojoule-class HEPW beam line with 1-30 picosecond pulse width to drive electron or proton cone-focused ignition experiments. Initial short-pulse capability on NIF is planned to be in place in the 2006 time frame.[60] Additional HEPW beams in a quad could be installed to provide multi-kilojoule capability.

8. NIF AS AN INTERNATIONAL SCIENCE CENTER

The first four beams of NIF have been activated. In the past year over 200 full system shots have been carried out on NIF. In addition a sophisticated suite of experimental diagnostics has been fielded on the 10-meter diameter target chamber and are available for use. These include static and gated x-ray imaging and streak cameras, full-aperture back scatter system, and a laser interferometer system for measuring shock velocities. The first physics experiments are already being performed on NIF. Initial experiments are studying laser-plasma interactions that are important for understanding the propagation of laser beams and the delivery of energy into ignition hohlraums. Other experiments are studying hydrodynamics of materials undergoing laser-driven shocks. Figure 23 shows results from a recent experiment directing NIF's first four beams with 16 kJ of ultraviolet light into a gas-filled target. The x-ray images compare favorably with sophisticated calculations. In the coming year, we are planning experiments to study materials equations of state and the hydrodynamics of shocked materials.

9. THE PATH FORWARD TO FULL NIF

Completion of all 192 laser beams is scheduled for September 2008. We have developed a plan for beam deployment that supports experiments with steadily increasing capability. Currently NIF is configured with four beams. We are preparing to build out the rest of the laser system beginning in FY 2005. The increasing symmetry and energy available as the number of beams increases enables a variety of target configurations including planar targets, horizontal and vertical half-hohlraums (halfraums), and vertical hohlraums with 4- and 8-fold symmetry. After project completion, NIF is expected to ramp up to approximately 700 shots per year for a wide variety of experimental users as a national user facility. A recent shot campaign on NIF provided three target shots per day over a three-day period, giving us confidence in NIF's ability to meet the planned 700 shots per year when it is fully operational. We have also developed a plan for fielding facility diagnostics that is synchronized to the increasing capability NIF provides.

In addition to diagnostics, the NIF Program includes support for building and commissioning facility capabilities in diffractive optics (phase plates), cryogenic target systems, and target area operations. We are developing a non-ignition cryogenic target capability to be fielded around the time of first cluster.

Some of the challenges to bringing NIF to its full capability include scaling control system software for bundle and cluster operations. The first tests of automated shot control for a bundle will take place in the coming year. As NIF continues its commissioning activities, significant progress is being made to optimize shot set up time. The first four beams of NIF are now routinely aligned in a parallel operation that takes about 15 minutes to complete.

Other factors that can impact NIF availability include optics quality and robustness, especially in the final optics section that transmits and focuses 3ω light to target chamber center. Significant progress has been made through dedicated research and development programs focusing on new manufacturing techniques for fused silica substrates, combined with new polishing techniques and thorough post-production annealing and mitigation techniques to ensure that NIF optics can meet all technical specifications at the highest design fluences.[6]

As NIF matures, we fully expect the facility to evolve to include exciting new capabilities, some of which are mentioned briefly here. The NIF laser system and support buildings have been designed with maximum flexibility for future enhancements such as multi-wavelength operation and high-energy short-pulse operation. NIF is ready to deliver the next generation of HED and ICF experimental capability for the US and international scientific communities.[61]

ACKNOWLEDGMENTS

This article reports on the accomplishments of over 3,000 men and women who have worked tirelessly to make NIF a reality. The authors are indebted to the contributions of everyone involved in the National Ignition Facility Project. This work was performed under the auspices of the U.S. Department of Energy by the University of California, Lawrence Livermore National Laboratory under contract W-7405-Eng-48.

REFERENCES

1. J. Lindl, *Inertial Confinement Fusion: The Quest for Ignition and Energy Gain Using Indirect Drive*, Springer-Verlag (1998).
2. *Laboratory Microfusion Capability Phase-II Study,* prepared by Interscience, Inc. for the Inertial Fusion Division Office of Research and Advanced Technology, ISI-TM9005281, May 31, 1990.
3. *Solid State Lasers for Application to Inertial Confinement Fusion (ICF),* W. F. Krupke, ed., Proc. SPIE **2633** (1995).
4. C. B. Tarter, "Inertial Fusion and Higher Energy Density Science in the United States," *Proc. 2001 Conf. On Inertial Fusion Science and Applications (IFSA 2001),* K. A. Tanaka, D. D. Meyerhofer, J. Meyer-ter-Vehn, eds., Elsevier, Paris (2002).
5. E. Moses, et al., "The National Ignition Facility: Status and Plans for Laser Fusion and High-Energy-Density Experimental Studies," Fusion Science and Technology, **43**, 420, (2003).

6. E. Moses, et al., The National Ignition Facility: The World's Largest Optics and Laser System, UCRL-151593-JC, SPIE Proc. Of Photonics West 2003: High-Power Lasers and Applications, Vol CDS81, July (2003).
7. M. L. Spaeth, "National Ignition Facility requirements and optical architecture," presented at LASE 2004, Photonics West, San Jose, CA, January 2004.
8. R. H. Sawicki, "National Ignition Facility: laser system, beam line design, and construction," presented at LASE 2004, Photonics West, San Jose, CA January 2004.
9. B. M. Van Wonterghem, "National Ignition Facility commissioning and performance," presented at LASE 2004, Photonics West, San Jose, CA, January 2004.
10. W. H. Williams, "Optical propagation modeling, W. H. Williams," presented at LASE 2004, Photonics West, San Jose, CA January 2004.
11. M. J. Shaw, C. A, Haynam, "National Ignition Facility laser performance operations model (LPOM," presented at LASE 2004, Photonics West, San Jose, CA, January 2004.
12. J. H. Campbell et al., "NIF advanced optical fabrication technology," presented at LASE 2004, Photonics West, San Jose, CA, January 2004.
13. T. I. Suratwala et al., "Neodymium glass," presented at LASE 2004, Photonics West, San Jose, CA January 2004.
14. C. J. Stolz et al., "National Ignition Facility transport optics," presented at LASE 2004, Photonics West, San Jose, CA, January 2004.
15. R. A. Hawley-Fedder, "NIF pockels cell and frequency conversion crystals," presented at LASE 2004, Photonics West, San Jose, CA January 2004.

16. D. W. Larson, “NIF laser hardware: the line replaceable units,” presented at LASE 2004, Photonics West, San Jose, CA, January 2004.

17. R. E. Bonanno, “Assembling and installing LRUs for NIF,” presented at LASE 2004, Photonics West, San Jose, CA, January 2004.

18. J. Wisoff et al., “Architecture and performance of the National Ignition Facility injection laser system,” presented at LASE 2004, Photonics West, San Jose, CA, January 2004.

19. C. D. Marshall, “NIF main laser system commissioning and performance,” presented at LASE 2004, Photonics West, San Jose, CA, January 2004.

20. P. A. Arnold et al., “Deployment, commissioning, and operation of plasma electrode pockels cells in the National Ignition Facility,” presented at LASE 2004, Photonics West, San Jose, CA, January 2004.

21. R. A. Zacharias et al., “National Ignition Facility alignment and wavefront control,” presented at LASE 2004, Photonics West, San Jose, CA, January 2004.

22. P. J. Wegner, “Final optics system: frequency conversion and beam conditioning,” presented at LASE 2004, Photonics West, San Jose, CA January 2004.

23. C. P. J. Barty, “High-energy petawatt lasers and NIF: motivations and challenges,” presented at LASE 2004, Photonics West, San Jose, CA, January 2004.

24. J. A. Paisner, J. D. Boyes, S. A. Kumpan, W. H. Lowdermilk, and M. Sorem, “Conceptual Design of the National Ignition Facility,” Proc. First International Conference on Solid State Lasers for Application to Inertial Confinement Fusion, Monterey, CA, May 31-June 2, 1995, SPIE Proceedings Series 2633, 2.

25. T. R. Boehly, R. S. Craxton, T. H. Hinterman, J. H. Kelly, T. J. Kessler, S. A. Kumpan, S. A. Letzring, R. L. McCrory, S. F. B. Morse, W. Seka, S. Skupsky, J. M. Soures, and C. P. Verdon, The upgrade to the OMEGA laser system, Review of Scientific Instruments, Vol 66(1) pp. 508-510, January (1995).
26. K. Mima, et al., Recent progress of implosion experiments with uniformity-improved GEKKO XII laser facility at the Institute of Laser Engineering, Osaka University, Physics of Plasmas, Vol 3(5) pp. 2077-2083, May (1996).
27. J. Campbell, et al., "Continuous melting of phosphate laser glasses," J. Non-Crystalline Solids 263&264 (2000).
28. J. Campbell and T. Suratwala., "Nd-doped phosphate glasses for high-energy/high-peak-power lasers," J. Non-Crystalline Solids 263&264 (2000).
29. S. Glenzer et al., Progress in Long Scale Length Laser-Plasma Interactions, submitted to the Proceedings of the Third International Conference on Inertial Fusion Sciences and Applications, Monterey, CA, September 2003.
30. P. Van Arsdall, et al., "The National Ignition Facility: Status of the Integrated Computer Control System," UCRL-JC-152832, submitted to the Proceedings of the International Conference on Accelerator and Large Experimental Physics Control Systems (ICALEPCS), Gyeongju, Korea, October 2003.
31. M. Newton et al., "Initial Activation and Operation of the Power Conditioning System for the National Ignition Facility," Proceedings of the International Pulsed Power Conference 2003, Dallas, TX, June 15-18, 2003.
32. C. Boley and M. Rhodes, "Modeling of Plasma Behavior in a Plasma Electrode Pockels Cell," IEEE Trans. Plasma Sci., Vol. 27, No. 3, June 1999.

33. J. Lindl, “Development of the Indirect-Drive Approach to Inertial Confinement Fusion and the Target Physics Basis for Ignition and Gain,” UCRL-JC-119015, Physics of Plasmas Vol 2(11) pp. 3933-4024, November (1995).

34. T. Parham, et al., “Developing optics finishing technologies for the National Ignition Facility”, Inertial Confinement Fusion Quarterly Report, Lawrence Livermore National Laboratory, UCRL-JC-129317, 177-191(1999).

35. D. Aikens, et al., “Developing Enabling Optics Finishing Technologies for the National Ignition Facility,” Lawrence Livermore National Laboratory, Livermore, CA UCRL-JC-129317, (1998).

36. P. Baisden, “National Ignition Facility (NIF) program update,” Lawrence Livermore National Laboratory, Livermore, CA UCRL-JC-137357, (2000).

37. J. Lawson, et al., “Surface figure and roughness tolerances for NIF optics and the interpretation of the gradient, P-V wavefront, and RMS specifications,” in Optical Manufacturing and Testing III, H. Philip Stahl, Editor, Proceedings of SPIE Vol. 3782, 510-517 (1999).

38. B. Stuart, et al., “Laser-induced damage in dielectrics with nanosecond to sub-picosecond pulses,” Phys. Rev. Lett., 74, p. 2248-51 (1995).

39. J. Menapace, et al., “Combined advanced finishing and UV laser conditioning for producing UV-damage-resistant fused silica optics,” SPIE Proceedings, Vol. 4679, p. 56-69 (2002).

40. R. Brusasco, et al., “Localized CO2 laser treatment for mitigation of 351-nm damage growth on fused silica,” SPIE Proceedings, Vol. 4679, p. 40-47 (2002).

41. C. Stolz, et al., “Fabrication of meter-scale laser resistant mirrors for the National Ignition Facility, a fusion laser,” submitted to the SPIE Proceedings of the International Symposium on Optical Science and Technology, Advances in Mirror Technology for X-ray, EUV Lithography, Laser, and Other Applications, 2003.

42. *Connecting Quarks with the Cosmos: Eleven Science Questions for the New Century,* National Research Council 2003.

43. B. Remington et al., “Materials Science at the Extremes of Pressure and Strain Rate,” submitted to the Proceedings of the Third International Conference on Inertial Fusion Sciences and Applications, Monterey, CA, September 2003.

44. Figure adapted from Figure 1.1 in *“Frontiers in High-Energy-Density Physics: The X-games of Contemporary Science,”* National Research Council 2003.

45. M.D. Perry et al., Rev. Sci. Instr. **70**, 265 (1999).

46. P. Celliers et al., “NIF as a Platform for High Pressure Shock Wave Equation of State Research,” submitted to the Proceedings of the Third International Conference on Inertial Fusion Sciences and Applications, Monterey, CA, September 2003.

47. *Frontiers in High Energy Density Physics: The X-Games of Contemporary Science*, National Research Council 2003.

48. B. Remington, “High Energy Density Astrophysics in the Laboratory,” *Proc. 2001 Conf. On Inertial Fusion Science and Applications (IFSA 2001),* K. A. Tanaka, D. D. Meyerhofer, J. Meyer-ter-Vehn, eds., Elsevier, Paris (2002).

49. R. Klein et al., Ap. J. 457, L85 (1996).

50. J.M. Foster et al., Phys. Plasmas 9, 2251 (2002).

51. B.A. Remington et al., Phys. Fluids B 5, 2588 (1993).

52. S. Haan, et al., “Update On Target Design for the National Ignition Facility,” Proc. 2001 Conf. On Inertial Fusion Science and Applications (IFSA 2001), K. A. Tanaka, D. D. Meyerhofer, J. Meyer-ter-Vehn, eds., Elsevier (2002).
53. R. McCrory, “Progress in Inertial Confinement Fusion Research in the USA,” submitted to the Proceedings of the Third International Conference on Inertial Fusion Sciences and Applications, Monterey, CA, September 2003.
54. S. Skupsky et al., “Advanced Direct-Drive Target Designs for the NIF,” submitted to the Proceedings of the Third International Conference on Inertial Fusion Sciences and Applications, Monterey, CA, September 2003.
55. M. Herrmann et al., “Exploration of the Parameter Space for NIF Ignition Capsules,” submitted to the Proceedings of the Third International Conference on Inertial Fusion Sciences and Applications, Monterey, CA, September 2003.
56. T. Bernat, “Target Technologies for X-ray Drive Ignition on the NIF,” submitted to the Proceedings of the Third International Conference on Inertial Fusion Sciences and Applications, Monterey, CA, September 2003.
57. L. Suter, “Prospects for High-gain, High-yield NIF Targets Driven by 2ω Light,” submitted to the Proceedings of the Third International Conference on Inertial Fusion Sciences and Applications, Monterey, September 2003.
58. R. Kodama, et al., “Fast Heating With a Petawatt Laser as a Step to Ignition,” submitted to the Proceedings of the Third International Conference on Inertial Fusion Sciences and Applications, Monterey, CA, September 2003.

59. P. Norreys, et al., "Advanced Fast Ignition Studies at the Rutherford Appleton Laboratory," submitted to the Proceedings of the Third International Conference on Inertial Fusion Sciences and Applications, Monterey, CA, September 2003.

60. C. P. J. Barty et al., "Technical Challenges and Motivations for High Energy Petawatt Lasers on NIF," submitted to the Proceedings of the Third International Conference on Inertial Fusion Sciences and Applications, Monterey, CA, September 2003.

61. For more information on the National Ignition Facility please visit the NIF web site at http://www.llnl.gov/nif

Figure Captions

Fig. 1. The National Ignition Facility at Lawrence Livermore National Laboratory.

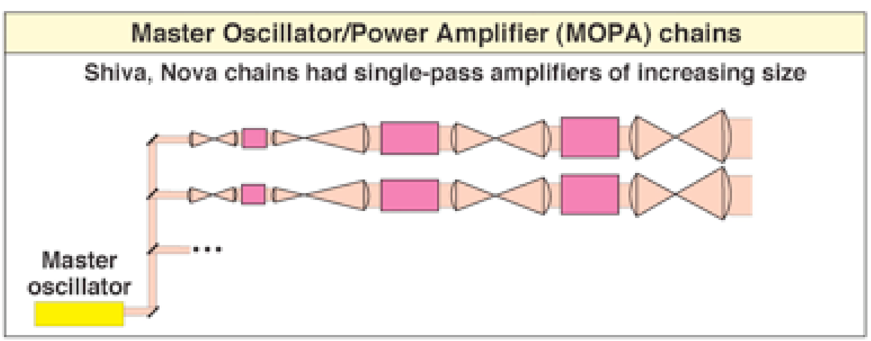

Fig. 2. A typical ICF single pass laser chain architecture for lasers designed in the time frame between the early seventies and the early nineties. Note that the clear aperture of the amplifiers increases as the beam moves down the chain.

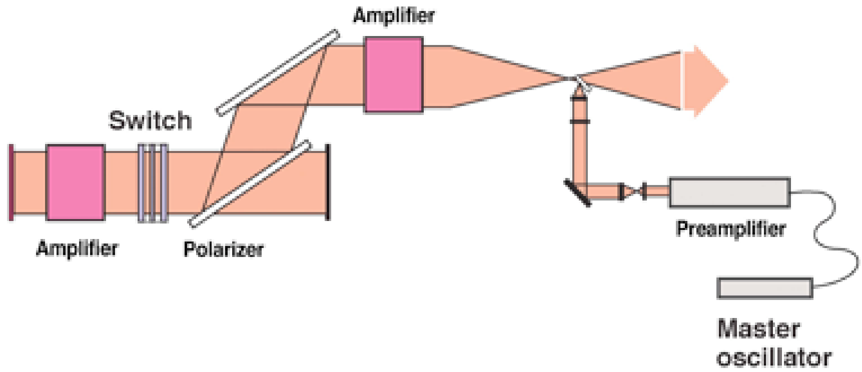

Fig. 3. A simplified view of the NIF multipass beamline design.

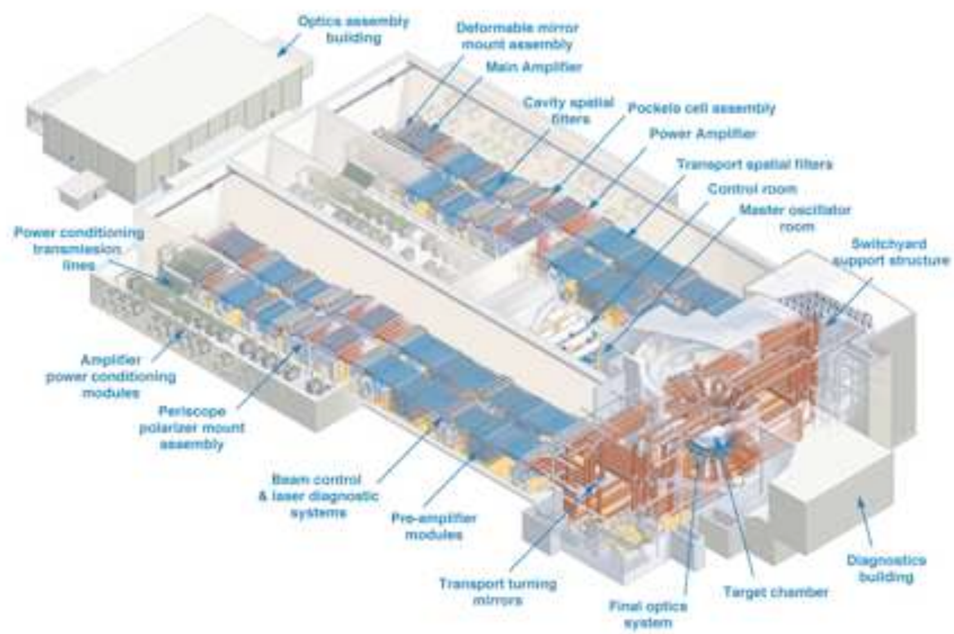

Fig. 4. Schematic view of the National Ignition Facility showing the main elements of the laser system. The 10-meter diameter target chamber sets the scale for the facility.

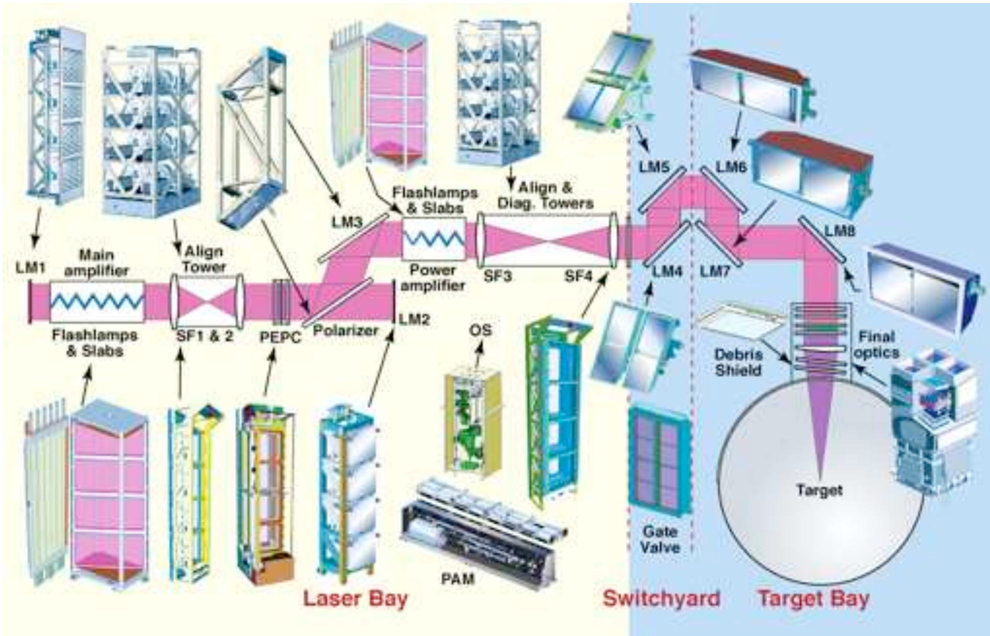

Fig. 5. Schematic representation of a NIF laser beam line showing the line-replaceable units used along the beam path.

Fig. 6. The NIF Master Oscillator Room (MOR) has been operating continuously since October 2001.

Fig. 7. NIF Preamplifier Module (PAM) undergoing testing in the Preamplifier Module Maintenance Area, which is located adjacent to the MOR in a dedicated Class 100 clean room facility.

Fig. 8. Laser glass slab and flashlamp cassettes, shown in the top left and right photographs are examples of NIF LRUs. The LRUs are inserted into the laser beampath using autonomous guided vehicles carrying portable clean canisters, shown in the bottom left photograph. One section of the assembled amplifier system is shown in the bottom right photograph.

Fig. 9. Plasma Electrode Pockels Cell LRU undergoing testing in the OAB.

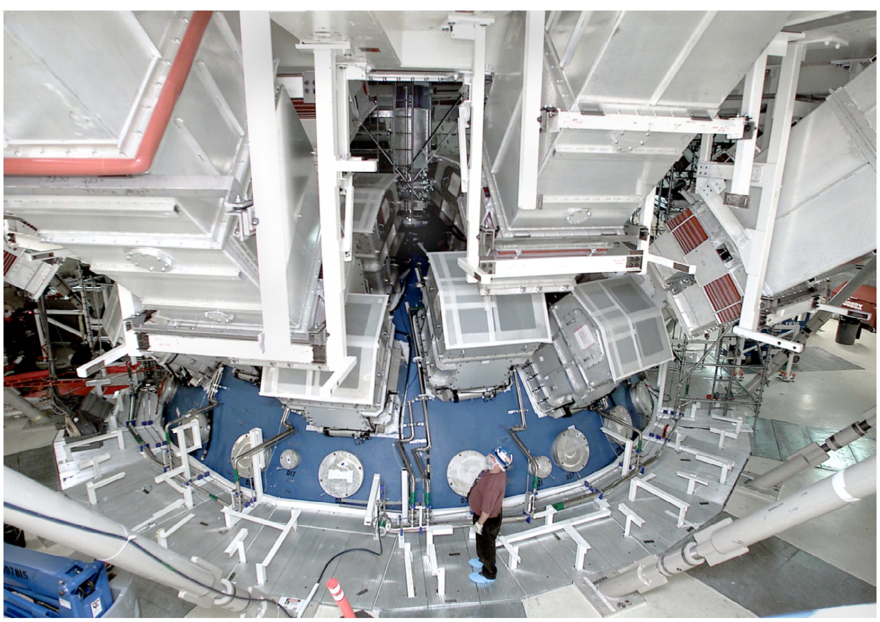

Fig. 10. Target chamber upper hemisphere showing 24 quads of beam tubes installed.

Fig. 11. The completed beampath for 96 laser beams in Laser Bay 2.

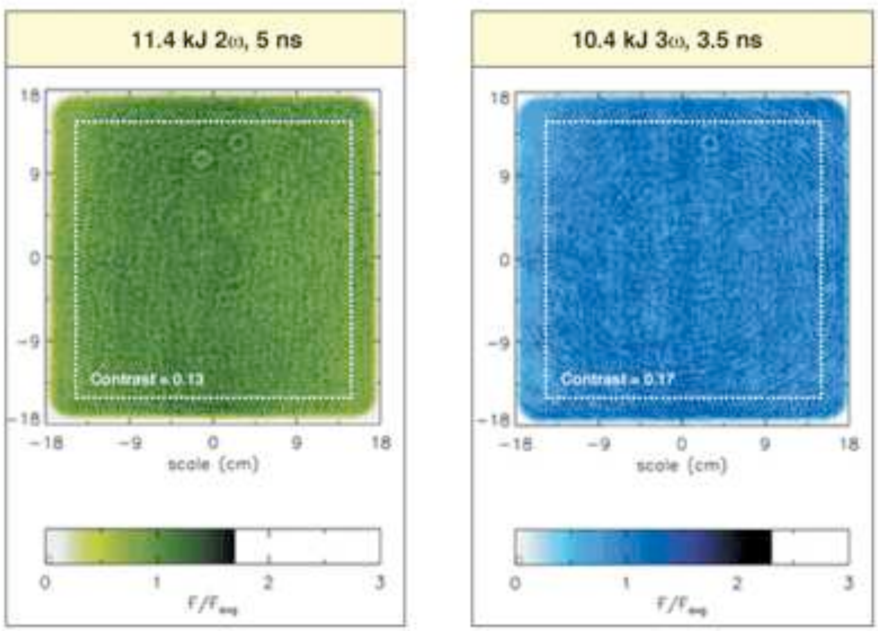

Fig. 12. Near field image of an 11.4 kJ 2ω and 10.4 kJ 3ω NIF beams showing excellent contrast uniformity, exceeding NIF's requirements.

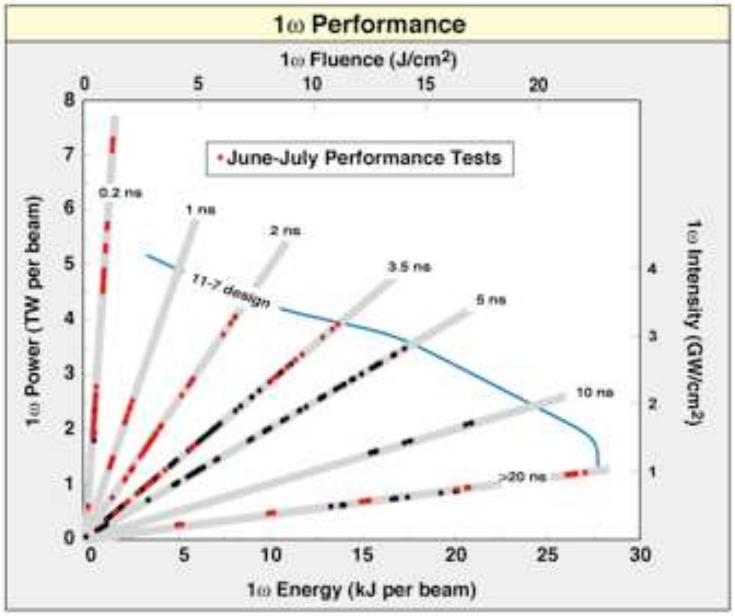

Fig. 13. 1ω energy vs. power is plotted for a number of NIF performance shots. The plot also indicates the level where energy and power is limited by the available number of glass slabs in the main amplifier (11 slabs) and the power amplifier (7 slabs).

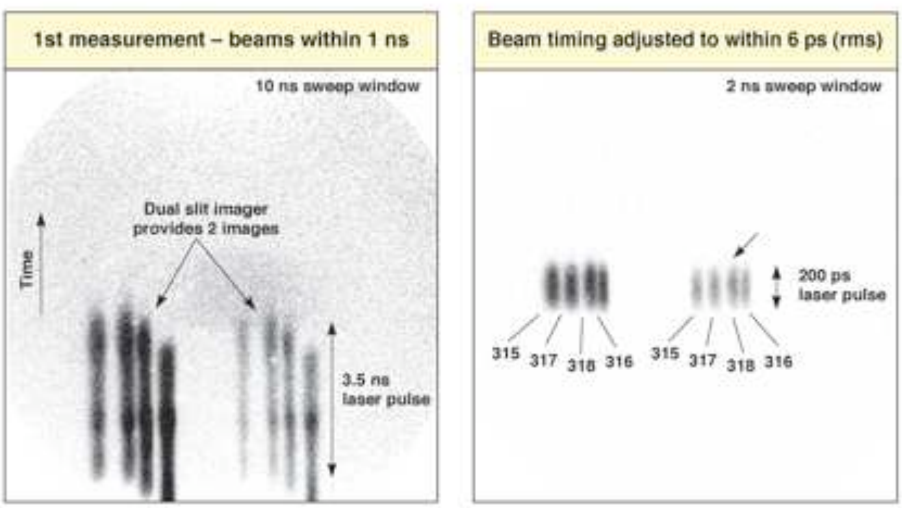

Fig. 14. Streaked x-ray images showing the beam-to-beam timing for a quad of four laser beams. Each image shows x-rays emitted from a target illuminated by the quad of beams and imaged through two different thickness filters.

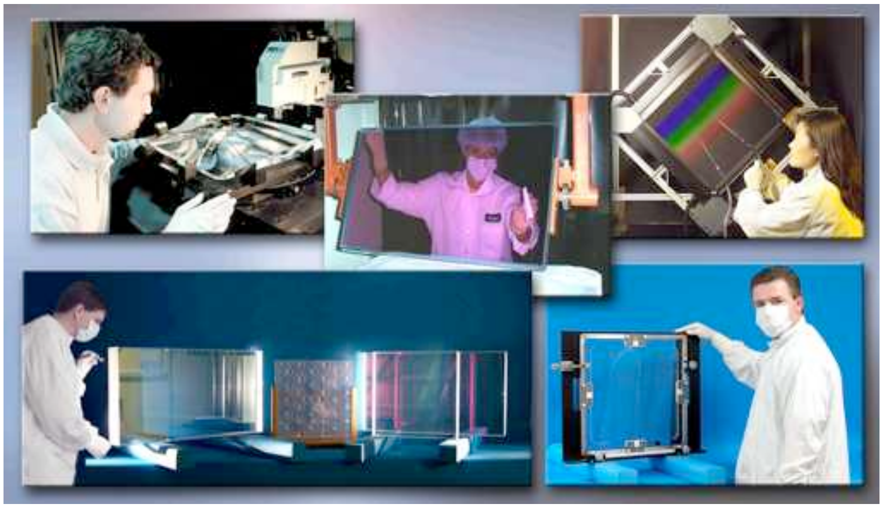

Fig. 15. Examples of large optics used on NIF. Clockwise from upper left: fused silica wedged focus lens, neodymium-doped phosphate laser glass slab, fused silica beam sampling grating, KDP frequency conversion crystal, and BK7 mirrors and polarizers.

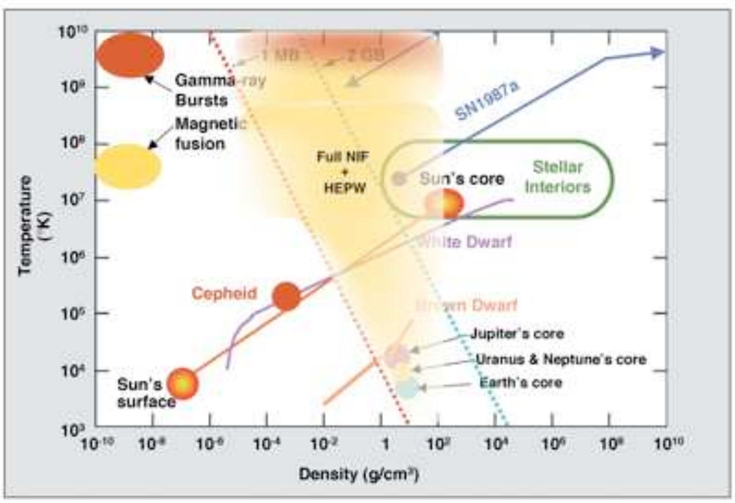

Fig. 16. High-energy density is a prevailing condition in astrophysics. This figure shows how NIF can reach conditions of extreme temperature over a range of material densities that are relevant to a variety of astrophysical phenomena. NIF, with high-energy petawatt (HEPW) short-pulse laser capability, can reach conditions approaching those in existence near the time of the Big Bang.[44]

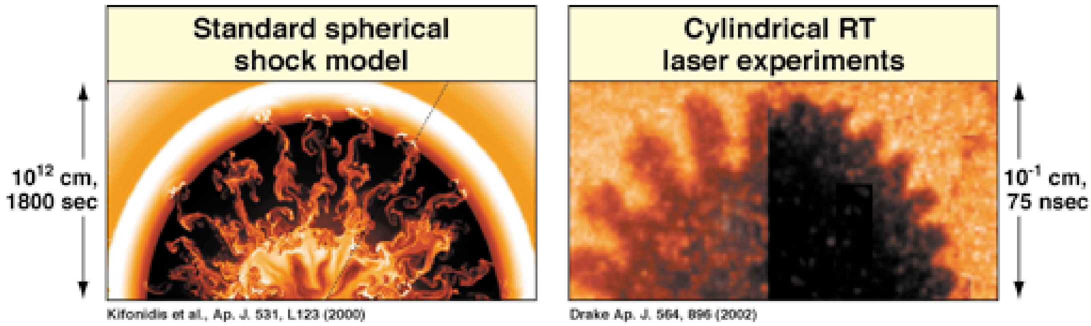

Fig. 17. Comparison of instabilities generated in a spherical shock model of supernovae, left, with RT experiments conducted using scaled targets driving by lasers. The image on the right show RT growth between 55 and 75 nsec on a scale of about 0.1 cm, that are qualitatively similar to the supernova model.

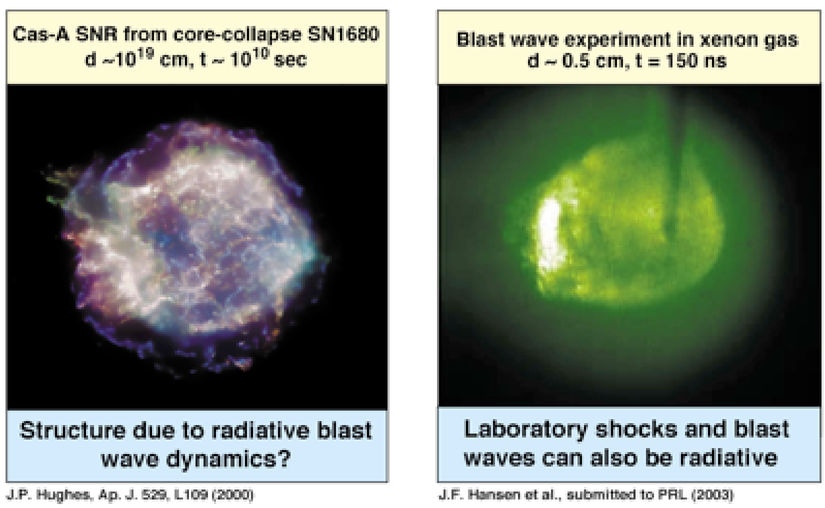

Fig. 18. Radiative shocks such as supernova blast waves can be simulated using scaled gas-filled targets illuminated by energetic laser beams. The photograph on the left is a Supernova Remnant (SNR) in Cassiopeia-A, which occurred in the year 1680 (Chandra X-ray Observatory photograph courtesy of NASA/CXC/SAO). In the image on the right, a beam incident from the left has initiated an expanding radiatively driven shock that is outrunning the material expansion from the target itself. This is seen as the faint glow surrounding the brighter inner sphere.

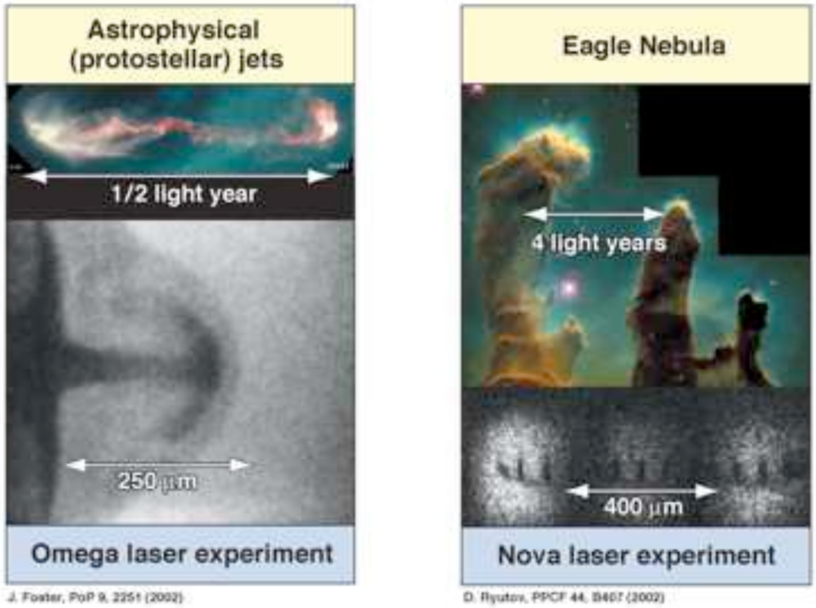

Fig. 19. Additional examples of scaled astrophysical phenomena that can be simulated using lasers. On the left is an astrophysical jet (Hubble Space Telescope photograph courtesy of NASA STSci, Release Number: STScI-PRC1995-24a) compared with a laser-generated jet using the Omega laser.[50] On the right the striking structures in the Eagle nebula (Hubble Space Telescope photograph courtesy of NASA STScI, Release Number: STScI-1995-44) are compared with similar RT structures generated using the Nova laser.[51]

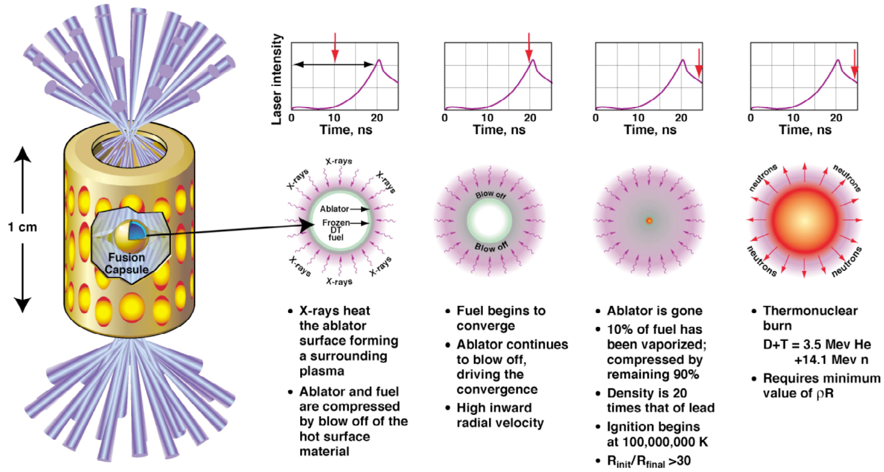

Fig. 20. A schematic representation of a NIF indirect-drive hohlraum target is shown on the left. NIF's 192 laser beams are grouped in 48 "quads" of four laser beams that are directed in opposite ends of the hohlraum to produce the x-ray drive. The time sequence on the right shows how the x-rays interact with the fusion capsule to create ignition and burn with energy gain.

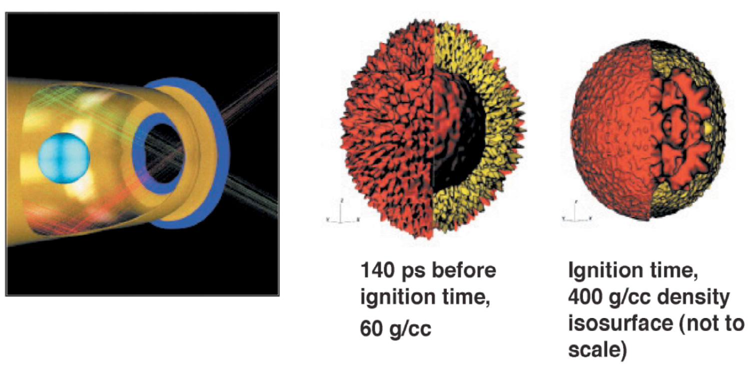

Fig. 21. Full 3-D calculation of capsule implosion showing ignition conditions predicted for a point-design NIF ignition target. This calculation used 12.8 million zones and 120 processors and produced a yield of 22 Megajoules. The figure at the left shows one half of the hohlraum with laser beams entering from the right. The figures at the center and right show two different views of the DT capsule as it is undergoing implosion.

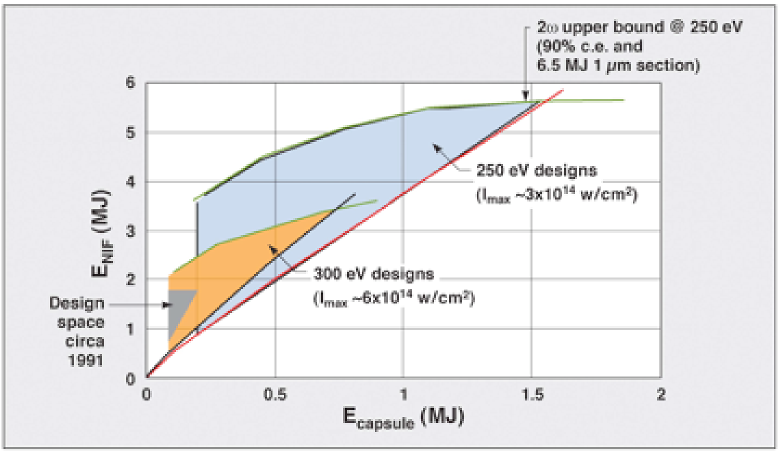

Fig. 22. Recent calculations of energy coupled to the capsule in the form of X rays converted from incident laser energy is shown in this figure. NIF's 1991 design space is shown in the lower left. The figure shows that the design space can be significantly increased for 2ω laser drive. Two extended regions show hohlraums driven to 300 eV and 250 eV, indicating that as much as 1.5 megajoules of x-ray drive energy may couple to a capsule at 250 eV temperature.

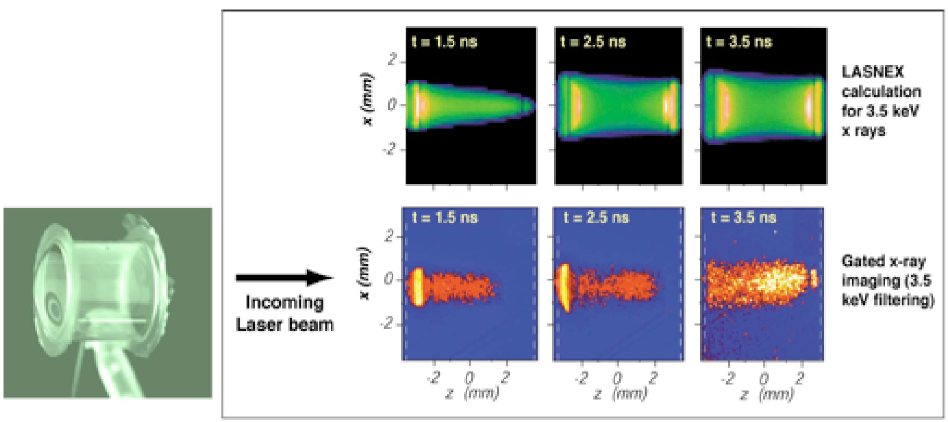

Fig. 23. Laser-plasma interaction experiments have been fielded on NIF using cm-scale CO_2 gas-filled targets, shown on the left. Results from the first physics experiments on NIF using these targets are shown on the right using a gated x-ray imaging diagnostic. This data can be compared with computer models that qualitatively agree with the data.

George H. Miller

Dr. George H. Miller is the Associate Director for National Ignition Facility (NIF) Programs at Lawrence Livermore National Laboratory (LLNL) and is responsible for the construction and operation the National Ignition Facility and the integration of the Inertial Confinement Fusion and High Energy Density Programs into the U.S. Stockpile Stewardship Program. NIF Programs Directorate also fosters the development of advanced laser science and technology for a wide array of applications.

During his 32-year career at LLNL, Dr. Miller has served in senior management positions with responsibility for national security programs and LLNL's nuclear weapons program, including research, development, testing, system analysis, weapons effects, weapons engineering, stockpile surveillance, and arms control. He was a principal developer of the Stockpile Stewardship and Management Plan to ensure the safety, security and performance of U.S nuclear weapons without full-scale nuclear testing.

Dr. Miller received his B.S. with high honors in Physics (l967), M.S. in Physics (l969), and Ph.D. in Physics (l972) all from the College of William and Mary, Williamsburg, Virginia. Dr. Miller holds memberships in the American Physical Society (APS) and Sigma Pi Sigma - National Physics Honor Society. He has received awards and honors from the National Science Foundation Graduate Fellowship, Gulf-General Atomics Fellowship, and Sigma Pi Sigma. He is a member of the USSTRATCOM Strategic Advisory Group (SAG) and Chairman of the Science and Technology Panel.

Edward I. Moses

In 1998, Dr. Edward I. Moses joined the National Ignition Facility (NIF) Project at the Lawrence Livermore National Laboratory and has served as Project Manager since 1999. Dr. Moses is responsible for the construction, installation, activation, and commissioning of the 192-beam NIF laser system and all of its associated support facilities and systems. In addition Dr. Moses provides overall integration between the NIF Project and the major user programs including the Inertial Confinement Fusion and High Energy Density Programs.

Dr. Moses also serves as the Principal Deputy Associate Director for NIF Programs Directorate. Before joining the NIF Project he led the Isotope Separation and Materials Processing Program at LLNL, while also serving as Deputy Associate Director for Lasers. Dr. Moses left LLNL in 1990, when he became the Executive Vice President of Advanced Technology Applications, Inc. He returned to LLNL as Assistant Deputy Associate Director for Program Development in the Physics and Space Technology Directorate, in addition to being the responsible manager for the PEREGRINE Cancer Therapy Program, a position he held until joining NIF. Dr. Moses began his career as a laser scientist and program manager at Hughes Aircraft Company in 1977 prior to coming to LLNL in 1980 as a manager in Laser System Operations and Laser Technology. Dr. Moses holds patents in laser technology and computational physics.

Dr. Moses earned his B.S. in Electrical Engineering from Cornell University in 1972 and his Ph.D. from Cornell University in 1977.

Craig R. Wuest

Dr. Craig R. Wuest is Assistant Associate Director for National Ignition Facility (NIF) Programs at Lawrence Livermore National Laboratory and Assistant NIF Project Manager. Prior to joining the NIF Project in 2000, Dr. Wuest led the Weapons Effect Group in the Nonproliferation, Arms Control, and International Security Directorate. During this time he chaired the NIF Radiation Science Users Group, a consortium of U.S. Department of Defense, National Nuclear Security Administration, and industrial contractors with interest in using NIF as an x-ray and neutron radiation effects simulator.

Dr. Wuest began his career at Lawrence Livermore National Laboratory as a post-doctoral researcher in the Laser Program and has managed programs in nuclear weapons and radiation effects, and high energy and nuclear physics detector development at the Superconducting Super Collider, Stanford Linear Accelerator Center, and the European Organization for Nuclear Research (CERN). He also served as an adjunct associate professor in the Physics Department at the University of California, Davis between 1994-1998.

Dr. Wuest received his B.A. (1978), M.S (1980), and Ph.D. (1983) in Experimental High Energy Physics from the University of California, Irvine. Dr. Wuest is a recipient of the 1989 Bruno Rossi Award in High Energy Astrophysics as a member of the U.S. IMB Collaboration for the discovery of the neutrino signal from Supernova 1987A. Dr. Wuest holds patents in electro-optical and nuclear instrumentation. Dr. Wuest also serves as a member of the staff of the US Strategic Command Strategic Advisory Group Science and Technology Panel.